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# Demonstrations of diode - pumped and grating - tuned $ZnSe:Cr^{2+}$ lasers

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**Abstract**

A diode-side-pumped $ZnSe:Cr^{2+}$ laser was operated with a 75 - Watt peak power 1.65 μm InGaAsP/InP pump array. The laser was configured with a "single-bounce" architecture to maximize its round-trip gain. Peak output powers of ~0.3 Watt were obtained with a 10% - transmitting output coupler and a lightly-doped crystal. The estimated "mode fill" of ~0.06 will increase with $Cr^{2+}$ concentration, raising the output power and extraction efficiency. With a grating tuner and $MgF_2:Co^{2+}$ laser pumping, the laser tuned throughout the 2134 - 2799 nm range.

**Keywords**

Rare earth and transition metal solid state lasers, Transition metal doped materials, Laser materials, Diode laser arrays, Infrared and far-infrared lasers

Within the last few years, the divalent-transition-metal-doped II - VI material class has been proposed as source of new tunable mid-IR lasers. These new lasers could presumably find many applications, including those currently filled by parametric oscillators, lead-salt diode lasers, etc. Spectroscopic evaluation[1] exposed $Cr^{2+}$ as a prime laser candidate on account of its high luminescence quantum yield and the expectation that ESA would be absent. ZnSe and ZnS were host media that gave laser action in a confocal cavity when pumped with a ~1900 nm $MgF_2:Co^{2+}$ laser;[2, 3] untuned operation centered around 2350 nm, the wavelength of maximum emission cross section. Three different doping methods (melt growth, seeded physical vapor transport, and diffusion doping) have produced $ZnSe:Cr^{2+}$ crystals that lase. Use of an intracavity birefringent filter initially allowed tuning throughout the 2280 - 2530 nm range. Several development opportunities remained to be addressed, including construction of a diode-pumped laser system,extension of the laser's tuning range, and improvement of the laser material quality (and hence, the slope efficiency.)

Spectroscopic parameters (see Table I) have a decisive impact on the choice of laser design. $ZnSe:Cr^{2+}$ has been referred to as "the Ti-sapphire of the mid-IR" on account of its similar electronic transition symmetry, short energy-storage lifetime (~9 μsec,) and broad emission linewidth (implying a wide tuning range of ~2000 - 3000 nm.) A salient difference is the much larger transition cross section, which, together with the longer fluorescence lifetime and smaller transition energy, combine to give a much smaller (by over two orders of magnitude) saturation intensity $\mathbf{I_{sat}} = h\nu/\sigma\tau \sim 14$ kW/cm$^2$. Generally, efficient laser operation mandates a pump intensity on the order of $I_{sat}$, although lower intensities also can work well in side-pumped configurations. The first $ZnSe:Cr^{2+}$ laser demonstrations were conducted in an end-pumped geometry

Table I. Spectroscopic properties of $Ti^{3+}$ in $Al_2O_3$ and $Cr^{2+}$ in II-VI hosts; the low $\mathbf{I_{sat}}$ value for the latter enables diode-pumped laser operation.

| | | $Ti^{3+}:Al_2O_3$ | $ZnSe:Cr^{2+}$ |
|---|---|---|---|
| Transition | | $^2E \rightarrow {}^2T_2$ | $^5E \rightarrow {}^5T_2$ |
| Upper-level lifetime | $\tau_{em}$ (μsec) | 3 | 9 |
| Peak fluorescence wavelength | $\lambda_{max}$ (nm) | 800 | 2300 |
| Fluorescence linewidth (RT) | $\Delta\upsilon$ (cm$^{-1}$) | 4300 | 1700 |
| | $\Delta\lambda$ (nm) | 300 | 1000 |
| Relative bandwidth | $\Delta\lambda/\lambda_{max}$ | 0.38 | 0.43 |
| Peak pump cross- section | $\sigma_{abs}$ (10$^{-20}$ cm$^2$) | 6.5 | 87 |
| Pump saturation intensity | $I_{sat}$ (kW/cm$^2$) | 2000 | 14 |

with a tightly-focused (~0.2 mm spot) $MgF_2:Co^{2+}$ laser beam, for a peak pump intensity well over 100 kW/cm$^2$, so laser threshold was easily reached. Upon "radiance conditioning," available diode arrays for the preferred 1.8 μm pump wavelength deliver more modest intensities of only a few kW/cm$^2$, so the low $I_{sat}$ value can be considered a crucial factor enabling efficient diode-pumped laser performance.

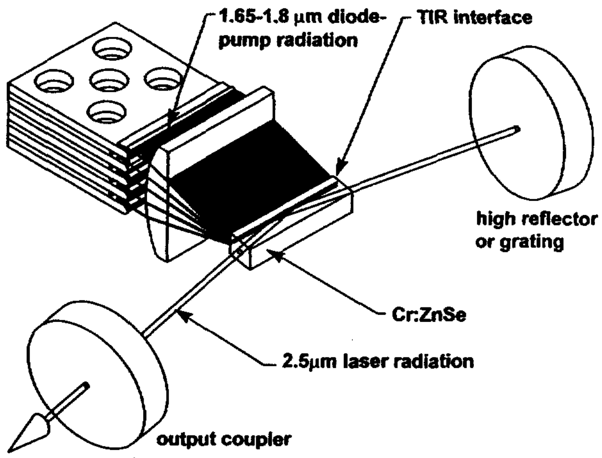


Fig. 1. Diode-side-pumped laser design, which facilitates integration of a ZnSe:Cr slab and a multiple-bar diode array.

Our diode-pumped laser design (Figure 1) is based on that of a previously-reported diode-pumped $Nd:YVO_4$ laser.[4] The output of four microlensed 1.65 μm InGaAsP/InP diode bars is combined in a cylindrical lens and focused onto a ~0.2 mm stripe on a ZnSe:Cr slab, whose end-faces are AR-coated for 2.5 μm. The single bounce at the "TIR interface" allows the resonated beam to sample the high-gain pump face region, yet enter and exit the crystal without aperture losses. Output energy and beam quality depend on the bounce angle and penetration depth of the pump light.[4] The diode array, when operated at a low duty cycle with a 50 μsec pulsewidth, gave the slope data of Figure 2; a maximum diode power of 75 W was obtained, and an array-integrated slope of 0.795 W/A corresponding to a slope for each diode bar of ~0.2 W/A. Slope-efficiency data for the integrated laser using a series of flat output couplers are shown in Figure 3. (The pump-energy scale has been normalized by a factor of 0.06,

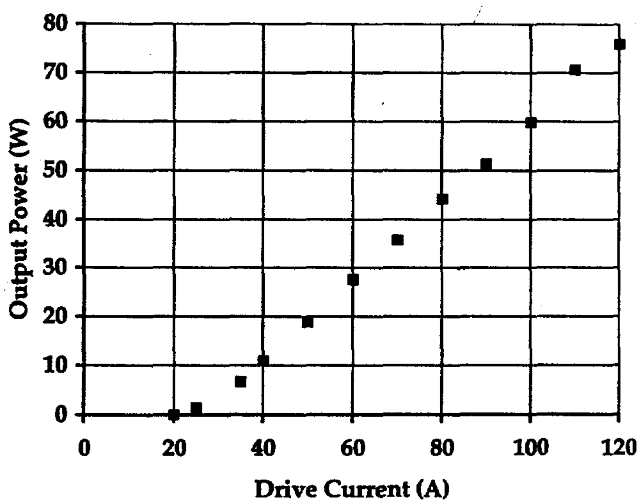


Fig. 2. Slope data for a 4-bar InGaAsP/InP pump array operating at 1.65 μm. The threshold and slope are respectively 24.4 A and 0.795 W/A.

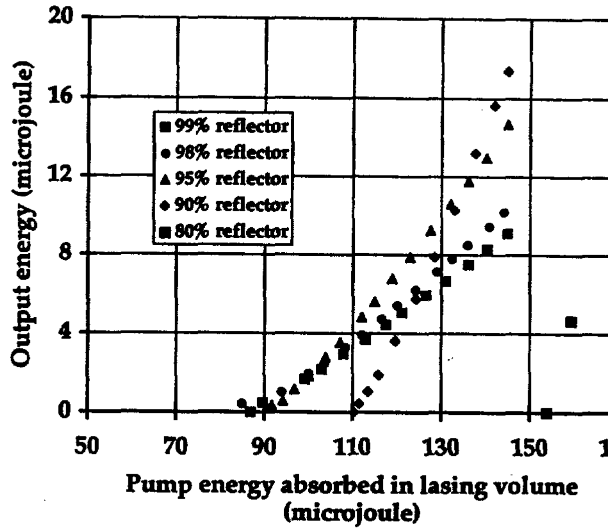


Fig. 3. Slope data for the diode-pumped ZnSe:Cr laser operating with several different flat output couplers. The pump-energy axis has been scaled to account for an estimated mode fill of 0.06.

roughly representing the fraction of the pump energy absorbed in one resonated-mode diameter. Our lightly-doped crystal had a 1.65 μm pump absorption coefficient of ~2.2 cm$^{-1}$, half the 1.8μm value of $\alpha_{max}$ ~ 4.4 cm$^{-1}$, associated with a $Cr^{2+}$ concentration roughly 5 x 10$^{18}$ cm$^{-3}$.) Here the threshold energy increases substantially for output coupling values above 10%, reflecting a crystal passive loss estimated at $\alpha_{loss}$ ~ 15%/cm. The maximum peak output power of 0.34W was achieved with the 90% -reflecting output coupler. A "figure of merit" **FOM** ≡ $\alpha_{max}/\alpha_{loss}$ can be used to describe crystal quality; in this case, FOM ~ 27. Our crystal - growth efforts are aimed at raising the doping level and pump absorption without increasing the passive loss. In general, we have found that the loss increases supra - linearly with the doping level, leading us to think that clustering of Cr ions may be a mechanism causing loss to appear. Virgin ZnS and ZnSe materials are prized for their extremely - high transparency and low absorption, even out to wavelengths as long as 10.6 μm, so there is something associated with Cr - doping that causes loss to appear.

Grating-tuning experiments were done by replacing the cavity high-reflector with a 420 line/mm diffraction grating on a rotation stage, and using curved output couplers. The diode array was removed and a pump beam from a

$MgF_2:Co^{2+}$ laser was focused onto the crystal using the same cylindrical lens. Since the $MgF_2:Co^{2+}$ laser has a low-divergence beam, its brightness is much higher than that of the diode array, making it easier to reach threshold with a lossy cavity element (i.e. grating.) Output wavelengths were checked with a monochromator. According to the tuning curve in Figure 4, the long-wavelength limit of operation appears to be ~ 2670 nm,

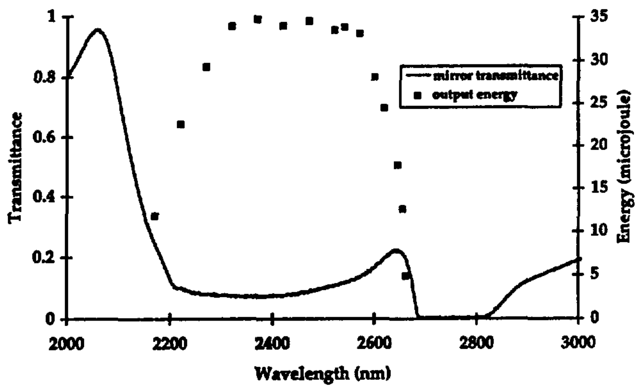


Fig. 4. Tuning characteristics obtained with $MgF_2:Co^{2+}$ laser pumping of ZnSe:Cr, resonated with a diffraction grating. The output - coupler transmittance spectrum reveals the OH absorption in the BK - 7 glass substrate material that blocked the laser's output from ~2650 - 2800 nm.

but in fact the OH - induced absorption in the BK - 7 mirror substrate blocked the laser output, which actually extended to 2799 nm. The short-wavelength cutoff was 2134 nm; even though the emission cross section remains substantial, self-absorption most likely inhibits laser operation. Higher-power pumping of this laser may well extend the tuning range at both the long- and short - wavelength ends.

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